ION GPS-94
September 20-23,1994

SESSION: UNIQUE APPLICATIONS

September 21,1994

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A NOVEL USE OF GPS FOR DETERMINING THE ORBIT OF A GEOSYNCHRONOUS SATELLITE: THE TDRS/GPS DEMONSTRATION

BIOGRAPHIES

Bruce ***Haines*** *received* his Ph.D. in Aerospace Engineering Sciences from the University of Colorado in 1991, after which he joined the Earth Orbiter Systems Group at JPL. He is a member of the Topex/Poseidon Joint Verification and GPS Precision Orbit Determination Teams, and specializes in precise orbit and geodetic analyses using GPS and in oceanographic applications of satellite altimetry.

Stephen M. ***Lichten*** received an A.B. degree from Harvard University in astrophysics in 1978 and his Ph.D. from the California Institute of Technology in 1983 (also in Astrophysics). He has worked at the Jet Propulsion Laboratory (JPL) since the summer of 1983 and presently is the Group Supervisor of the Earth Orbiter Systems Group and a manager in the NASA Deep Space Network Advanced Systems Program, He has focused his efforts recently on high-accuracy satellite orbit determination applications, emphasizing precise GPS tracking. As part of the GPS flight experiment on Topex/Poseidon, his group recently developed a capability for routine "orbit determination accurate to better than 3 cm in altitude for Topex.

Ronald ***Muellerschoen*** received a B.S. degree in physics at Rensselear Polytechnic Institute and a M.S. degree in applied math at the University of Southern California, He is currently a Member of the Technical Staff in the Earth Orbiter Systems Group at the Jet Propulsion Laboratory (JPL). His work at JPL has concentrated on 'the development of efficient, filtering/smoothing software for processing GPS data and the processing of Topex/Poseidon-GPS data.

Don ***Spitzmesser*** has worked at JPL since 1969. He received a B.A. in mathematics from Cal State L.A. in 1972. While at JPL, he has worked on numerous NASA missions, including Lunar Orbiter, Surveyor, Mariner. He has been in the GPS Systems Group since 1980 where he helped in the development of the SERIES, SERIES-X, Rogue, and TurboRogue GPS receivers,

Jeffrey ***M. Srinivasan*** received the Bachelor of Arts in Engineering and Applied Sciences degree with honors from Harvard University in 1983 and the Master of Science in Electrical Engineering degree from University of Southern California in 1988. He joined the technical staff at the Jet Propulsion Laboratory in 1983. He is currently a Technical Group Leader and has been the lead hardware /software engineer on the Rogue/TurboRogue GPS receiver projects. He has designed custom digital integrated circuits (ICs) and developed of signal processing algorithms for GPS applications. He is currently adapting of the acquisition algorithms and system software of the TurboRogue GPS receiver for various GPS and non-GPS applications.

Dennis Sweeney received a BSEE in 1971, M.S. in EE in 1984, and Ph.D. in EE in 1992 from Virginia Tech, where he also taught for a number of years as an Assistant Professor. His research included study of adaptive power control on satellite links as a fade counter measure, propagation studies, and RF circuit design. He joined JPL's GPS Systems Group in 1993. He returned to Virginia Tech in 1994, where he presently holds a research position.

Larry *Young* received his Ph.D. in Nuclear Physics from the State University of New York at Stony Brook in 1975, and has worked at JPL since 1978, currently as a technical group supervisor working on the development of high precision radio inter ferometric techniques for spacecraft navigation and geodesy. He led the development of various techniques to reduce instrumental errors in VLBI measurements, and to demonstrate nanosecond level clock synchronization with both VLBI and GPS. He has worked on the design and development of several high precision GPS receivers, and on novel applications of precision GPS to problems of scientific interest. He has initiated work on custom GaAs chip design to enable improved radiometric performance, and has worked with system studies aimed toward improving the performance of spacecraft ranging systems.

ABSTRACT

New GPS-based techniques for tracking high Earth orbiters are under evaluation at the Jet Propulsion Laboratory (JPL). One promising approach dispenses with the GPS flight receiver, employing instead a simple beacon on the user spacecraft. The beacon signal can be tracked along with signals from the GPS spacecraft in a GPS ground receiver. This approach, hereinafter referred to as GPS-like tracking (GLT), exploits GPS to precisely determine station coordinates, and media delays and to provide clock synchronization at the ground stations. An experiment was undertaken by JPL in January 1994 to demonstrate how GLT could contribute to determining orbits of the geosynchronous Tracking and Data Relay Satellites (TDRS). In this paper, we will describe initial results from this experiment.

INTRODUCTION

Among the more demanding of GPS applications is precise positioning of Earth orbiters. It has recently been demonstrated that orbits for the Topex/Poseidon oceanographic satellite could be determined to better than 3 cm (rms) in the radial direction using GPS [1]. This result can be attributed in large part to the continuous tracking and multi-directional observing geometry afforded by GPS in the 1,340 km altitude orbit occupied by Topex/Poseidon. At higher altitudes, visibility of the GPS signals begins to degrade. Above the GPS constellation (12,200 km), it becomes necessary to look in the nadir direction to see any GPS signals and the geometry becomes increasingly poor as the user satellite moves away from the Earth, At first it is tempting to discount the need for precise positioning services at these extremely high altitudes. More careful consideration, however, reveals that there are many potential customers represented in the geosynchronous spacecraft orbiting at an altitude of 36,000 km.

The notion that GPS can be used to provide or assist in the determination of geosynchronous satellite orbits is not new, Building on a heritage of Very-Long Baseline Interferometry and other deep-space tracking techniques, scientists at the Jet Propulsion Laboratory recognized over a decade ago that GPS could be exploited to synchronize clocks and calibrate media delays to support positioning of geosynchronous satellites [2]. An extension of this concept which relied on the tracking of signals from high-Earth orbiters within a GPS receiver was advanced soon thereafter [3], *Wu [4] performed* a more detailed analysis of this strategy, and also considered a scenario wherein a GPS flight receiver would be included on board the spacecraft.

A logical candidate for testing these techniques is NASA's Tracking and Data Relay Satellite System (TDRSS). This system, whose space segment currently consists of 5 geosynchronous orbiters, is used by NASA to support positioning and data relay activities for a wide variety of Earth orbiting spacecraft [5]. Accurate real-time positioning of the TDRSS spacecraft is fundamental to the proper operation of the system, and is achieved via the relay of coherent signals through unmanned transponders at the remote tracking sites. These remote beacons are collectively referred to as the Bilateration Ranging Transponder System (BRTS). Range and Doppler observations from BRTS are routinely scheduled from the central ground facility at White Sands, New Mexico. These data are subsequently used in conjunction with models of the forces perturbing the spacecraft motion to determine the TDRS positions, Evaluation of the TDRS ephemerides suggests that orbit consistency is maintained to better than 70 m using the operational BRTS method [6]. This level of precision is adequate for current applications; however, the technique requires valuable TDRS antenna time that could otherwise be used for servicing user spacecraft.

In recognition of the need for improved tracking for future TDRS applications, a number of alternative methods have been explored [e.g., 7-1 2]. The demand for improved accuracies provides an important motivation for these efforts. This requirement, however, is balanced by the appeal of a simple, low-cost and autonomous system that requires no disruption of TDRSS user services and delivers the ephemerides in near real-time. GPS-based techniques hold great promise for helping to meet these sometimes conflicting demands, Before describing our experiment, it is instructive to review some general characteristics of GPS-based tracking and of short-baseline interferometry, both of which are important elements of our system.

GPS-LIKE TRACKING

In this paper, we examine a technique based on tracking the existing TDRS telemetry down link (14 GHz) in GPS receivers. This method, hereinafter referred to as "GPS-like tracking" (GLT), exploits GPS measurements to provide calibration of clock and media delays, As commonly envisioned, GLT involves the use of a small global network of ground stations that track simultaneously GPS signals and a broad-beam beacon signal originating from the user satellite (Figure 1). Covariance techniques have been adopted in previous studies to explore the suitability of this technique for the advanced follow-on to the present TDRS [e.g., 4,8,12]. These studies assumed that the beacon signal of the advanced TDRS would be tailored for the GLT application, illuminating the Earth in the same manner as the GPS signals and thus permitting common visibility from widely dispersed stations,

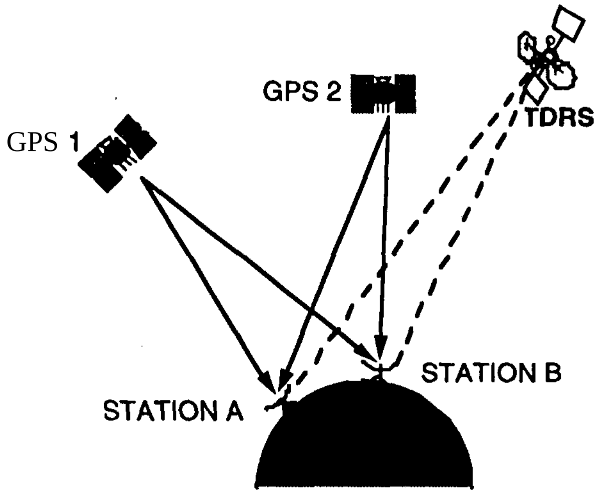

Fig 1. Differential **GPS-like** tracking (GLT) **applied** to TDRS. Four simultaneous **observations of GPS carrier phase and pseudorange enable removal of transmitter and receiver clock offsets. After tracking for 12-24 hours, theGPS orbits can be determined to a few tens of centimeters. In GLT, the carrier phase of the high-Earth orbiter is also included and its orbit similarly estimated.**

This is the essence of the system used to compute ephemerides for the GPS spacecraft with **root-mean-**square **(RMS)** errors of a few tens of centimeters [1 3]. If a GPS spacecraft were simply moved to a geosynchronous orbit, it is sensible to expect that the nearly same level of orbit accuracy could be achieved. The TDRSS in orbit today do not broadcast **GPS-like** signals, precluding the possibility of achieving comparable results with **GLT.** Fortunately, the requirement for orbit accuracy (50 m) is much less stringent, allowing us to consider other options, In this paper, we describe a GLT technique which uses short baselines, drawing its heritage from the method of Connected Element **Interferometry (CEI).**

SHORT BASELINE TRACKING

One attraction of using the existing TDRS Ku-band space-to-ground link **(SGL)** for orbit determination **is that** the signal is always present when the TDRS satellite **is an** operational mode (i.e., the TDRS is supporting user services). The beam from the **SGL** antenna can therefore be monitored passively from the ground, Unlike BRTS, there is no impact on the scheduling of the other TDRS spacecraft antenna to support user satellites. What makes the use of the SGL challenging for precise orbit determination applications is its narrow **beamwidth:** the down link illuminates *only* a limited region of the southwestern U.S. **surrounding** the TDRSS White Sands Ground Terminal (WSGT). The size of the SGL footprint (compare Figure 2) precludes the use of long, continental baselines for orbit determination. Since the angular sensitivity y of the tracking measurements are proportional to the baseline length, good performance with short baselines requires extremely tight control of delay errors. Most important in 1-way measurement systems (e.g. interferometry) is the clock, since an error of only 1 nsec is equivalent to 30 cm in path delay. Synchronization of **interferometric** measurements can be achieved by physically connecting the tracking stations, e.g. with fiber optics, to ensure that a common clock is used to register all the observations. Atmospheric delays are also problematic, but are somewhat mitigated owing to the proximity of the stations.

A specialized form of **interferometric** tracking using short baselines has **been** studied for possible application to the TDRS orbit determination problem [e.g., 2,7], Envisioned for this technique, known as **Connected** Element **Interferometry (CEI),** is an array of tracking stations near White Sands connected by fiber optics. The distributed clock would allow **very** precise measurements of the differential phase of the SGL signal broadcast by TDRS and observations of stellar sources (quasars) could be used for calibrations and resolution of the phase ambiguities. A prototype connected element interferometer has been installed over a 21 km baseline at the JPL Deep Space Network **(DSN)** site in Goldstone, California, Preliminary tests of this system using data from the **Magellan** Venus orbiter suggest that angular accuracies of 50-100 nrad are achievable under ideal conditions [14]; this is equivalent to 2-4 m at geosynchronous altitude,

For TDRS applications, ***Nandi*** *et al.* [1 1] suggested an alternative to **CEI** that is operationally simpler and does not require a capability to **record** quasar signals, Their method relies on monitoring only the **station-differenced** carrier phase, i.e. the integer cycle ambiguities are not resolved. These so-called short baseline difference carrier phase **(SBΔΦ)** measurements determine the change in plane-of-sky position of the TDRS spacecraft. The angular resolution of the data are given by $\Delta\theta = \Delta\phi / B\sin\theta$ where θ is the angle between the baseline and the transmitter, B is the baseline length, and ϕ is the precision of the difference phase measurement,

When included in a dynamical orbit determination, the **SBΔΦ** measurements can determine 5 of 6 **components** of the TDRS state vector. The longitude of the orbit—or the satellite's down-track position in inertial coordinates—is poorly determined. To solve for this component of the orbit, a few range measurements are needed. While the ensemble of range and SBΔΦ measurements provide somewhat weaker position information than CEI observations, covariance studies suggest that application of this technique could provide orbits readily satisfying the 50 m accuracy requirement for TDRS assuming the presence of a well-calibrated ranging system at White Sands [11].

GLT OVER SHORT BASELINES

Testing a connected element network for TDRS at White Sands would be somewhat cost prohibitive, since a full demonstration would require the establishment of two or three tracking stations connected by fiber optics. It is logical to inquire whether an alternative system based on GPS could satisfactorily control the delays and eliminate the need for connected elements and expensive calibration devices. Indeed, when one considers the potential sources of delay error in a short-baseline tracking scenario, one realizes quite remarkably that they are all amenable to being measured with GPS: a) *Clock synchronization;* Routine processing of GPS data for the International GPS Service (IGS) are providing clock synchronization at tracking stations dispersed around the globe to better than 1 nsec [15-16]. Better control of clock errors can be expected over short baselines owing to cancellation of commons errors. b) *Station coordinates:* Geocentric station coordinate solutions accurate at the cm level are generated on a daily basis [17] c) *Atmospheric delays;* Zenith wet troposphere delay can be measured with an accuracy that rivals that achieved by radiometers [18]. The dual-frequency nature of the GPS signal also allows calibration of the ionosphere delay, but this effect is quite small for the 14 GHz SGL from TDRS.

In our experiment, precision geodetic-quality GPS receivers were adapted to track TDRS and GPS simultaneously and were used in lieu of a connected element network. This technique, which blends certain aspects and offers advantages of, both GLT and SBΔΦ [19], is the essence of the TDRS tracking experiment described in this paper,

EXPERIMENT CONFIGURATION

The TDRS/GPS tracking demonstration took place from January 16-22, 1994, GPS and TDRS satellites were tracked simultaneously from three sites: El Paso, TX, Socorro, NM, and Pasadena, CA (Figure 2). Initially we planned to deploy the three receivers within approximately 100 km of the TDRS tracking station at White Sands, NM. In view of logistical considerations for this proof-of-concept demonstration, we elected instead to keep one station at JPL. Proximity to the GPS laboratory at JPL allowed us to readily test fixes or upgrades on this station should problems have developed over the course of the experiment. This configuration also permitted us to test the performance of side-lobe tracking, as JPL is in a fortuitous location that placed it in the first side lobe of the SGLS from both TDRS-5 (1 75° W) and TDRS-3 (62° W). The other two stations, operated from motel rooms in El Paso and Socorro, were within the main beam of the SGL of both TDRS-3 and 5.

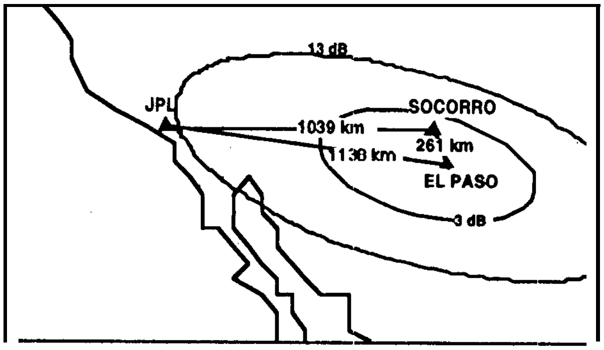

Fig 2. Configuration of TDRS/GPS tracking network. The footprint of the TDRS-3 space. to-ground link (SGL) during the January 1994 experiment is shown.

The setup at each tracking terminal consisted of an advanced GPS TurboRogue receiver [20], a Dorne-Margolin omni-directional GPS antenna, a small directional horn antenna (opening dimensions 17 X 14 cm) and Ku- to L-band down converter for tracking the 14 GHz TDRS SGL. The TurboRogue receiver, developed at JPL, is essentially a compact, precision digital radiometric tracking system. About the size of a dictionary, the receiver can measure the phase of a tone (e.g. the GPS carriers) with an precision equivalent to a small fraction of the wavelength, At this writing, there are over 50 Rogue and TurboRogue receivers distributed around the globe; data from these stations are used for precise GPS orbit determination and a variety of geodetic and tectonic studies [13]. For this experiment, each of the three receivers was modified at JPL to track 7 GPS spacecraft (L-band carrier phase and pseudorange) and one TDRS spacecraft (Ku-band SGL carrier phase) simultaneously (Figure 3).

DATA

Data collection commenced on January 16 with tracking of TDRS-3. Also known as TDRS-Central, this spacecraft was seen at an elevation of approximately 30° when viewed from WSGT. TDRS-3 was tracked for nearly 5 days before the stations were reconfigured to track TDRS-5 (January 21). This spacecraft presently occupies the western slot and is seen at an elevation of only 10° from WSGT. Although the TDRS-5 track spanned only 18 hours, this session was useful for understanding the effects of tracking at lower elevations. Depending on the station, 85–95% tracking coverage was achieved over the course of the experiment, The largest data outage occurred on Jan. 18 when the TDRS-3 SGL was switched off for approximately 7 hours to support an antenna maintenance activity at White Sands. All three sites did experience a significant number of phase interruptions over the duration of the experiment: the longest period of time during which all three stations tracked without a single loss of lock was about 20 hr. We believe that the number of phase breaks can be reduced in future demonstrations with changes to the receiver configuration,

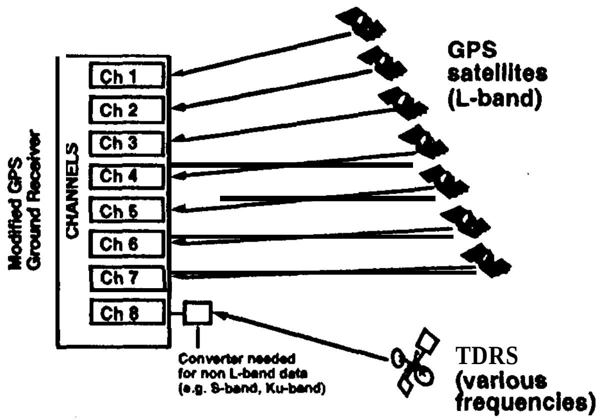

Fig 3. Schematic for the GPS ground receiver modified to simultaneously track TDRS along with GPS satellites. For the TDRS SGL, which is at 14 GHz, a small separate antenna with down converter was added to the GPS ground instrument

Figure 4 depicts a sample the raw TDRS-3 data from each of the three sites. The top panel gives the raw phase measurement converted to a biased 3-way range (White Sands to TDRS-3 to GPS terminal) and the bottom panel gives the signal-to-noise ratio, The range data show the expected diurnal signature from the geosynchronous TDRS orbits. For TDRS-3, the peak to peak variation of the 3-way range was -200 km, while for TDRS-5 (not shown) the variation was only -30 km. This disparity is attributable primarily to the different orbits occupied by the spacecraft: TDRS-3 was inclined by 0.7° relative to the equator, while the TDRS-5 inclination was only 0.06°, The TDRS-3 orbit was also slightly more eccentric. Also worthy of note in Figure 4 is the lower characteristic SNR for the JPL station. This reflects the decrease in signal strength associated with observing the SGL in the side lobe of the antenna pattern.

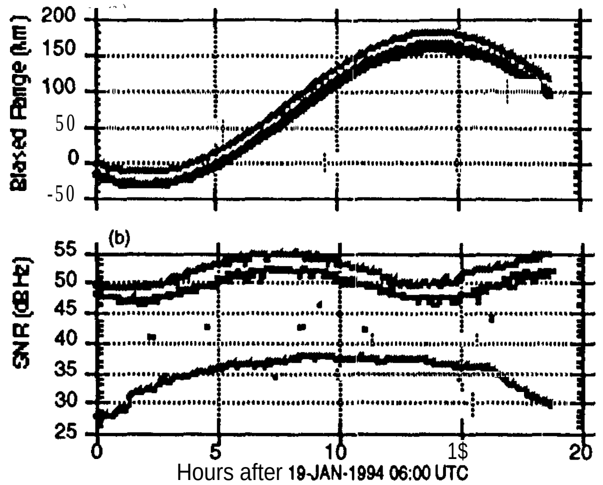

Fig 4. Biased range (Panel A) and signal-to-noise ratio (Panel B) from TDRS -3 carrier phase tracked at JPL, El Paso, and Socorro on January 19,1994. The station with the iow SNR is at JPL, which tracked TDRS-3 from within the first sidelobe.

As explained previously, ranging information to TDRS is needed to fix the longitude of the spacecraft, To satisfy this requirement, we used range observations from routine Tracking Telemetry and Control (TT&C) activities at White Sands. These observations are based on tracking of the K-band SGL with 18-m antennae located at the central ground terminal. The range data are used along with az-el observations for routine station keeping and mission planning at WSGT, but are not intended for precise orbit determination (a service which is presently provided by the BRTS system). As such, the data can contain large systematic biases that, without calibration, preclude achievement of 50-m accuracy in determining the longitude of the TDRS orbits. In order to estimate these biases, we calibrated the TT&C range data against the precise TDRS orbits generated at Goddard Space Flight Center (GSFC) using the BRTS system. Shown in Figure 5 are the residuals of the TT&C range with respect to the BRTS-derived orbits for TDRS-3 over the course of the experiment, Biases as large as 50 m (l-way) can be seen. This may reflect uncertainty in station coordinates and errors in the BRTS orbits, as well as calibration delay errors, *Nandi et al.* [11] indicating that a lo-m range bias could translate into a 70-m error in the longitude component of the TDRS orbit depending on the geometry, so proper calibration of the ranging system is of obvious importance, For the present analysis, we computed orbits both with the raw (i.e., uncalibrated) data and with the biases removed.

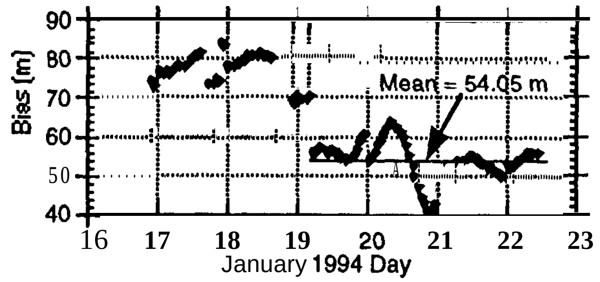

Fig 5. Residuals of White Sands TDRS-3 range data with respect to BRTS-derived orbit from Goddard Space Flight Center. A 1-way bias of 54.1 m wasused inthis study to calibrate the TDRS-3 range data for periods after 06:00 UTC on January 19,1994.

SOLUTION STRATEGY

The unified TDRS/GPS orbit solutions were computed using the GIPSY/OASIS II software [20]. This package is also used at JPL to compute GPS orbits for the International GPS Service (IGS) with root-mean-square (rms) accuracies of a few decimeters [13], and Topex/Poseidon orbits with rms radial accuracies of better than 3 cm [1], The assumptions comprising our solution strategy reflect guidelines advanced by NASA for operational TDRS orbit determination. These guidelines represent a compromise between accuracy and timeliness, We adopted 50 m (1 σ, total position) as the figure of merit for accuracy. We assumed that this level of accuracy should be met in normal operations with about one-days worth of tracking,

Table 1 outlines the solution strategy. With the exception of a few elements that are not consistent with a real-time solution, the strategy mirrors that presently used at JPL in the routine processing of GPS data from the global IGS network, In particular, zenith wet troposphere delays were estimated as stochastic random-walk parameters and station clock offsets were estimated as stochastic white noise processes at each measurement batch. The white-noise clock approach is analogous to (but more general than) explicit double differencing between stations and satellites. Satellite states for the TDRS and all GPS spacecraft were estimated, with a-priori for the latter coming from the broadcast ephemerides, Inasmuch as the GPS data are collected at only three ground stations, and they are quite close, the GPS orbit errors are undoubtedly nonuniform over the globe. This is inconsequential to the success of this study, GPS provides clock synchronization and media calibration for our network surrounding White Sands. In this context, regional improvement of the GPS orbits suits our purposes quite well.

TABLE 1. ESTIMATION STRATEGY FOR GPS/TDRS ANALYSIS

Data Noise (150s observations)	
GPS carrier phase	1 cm
TDRS carrier phase	1 cm
GPS pseudorange	30 cm
TDRS 2-way range(1/hr)	5 m noise 1-30 m bias
A-priori for estimated parameters	
TDRS position (X, Y, Z)	100 km
TDRS velocity (X, Y, Z)	1 In/s
TDRS solar radiation pressure coeff.	100940
TDRS carrier phase biases	1s
GPS position (X, Y, Z)	100 km
GPS velocity (X, Y, Z)	1 M/s
GPS carrier phase biases	1s
GPS spacecraft clock errors	1 s white
TurboRogue station clock errors [1]	1 s white
White Sands station clock error	1 s white
TurboRogue Zenith wet troposphere	40 cm +5 cm/$\sqrt{day}$ random walk
1 El Paso clock fixed	
Models and constants	
TDRS solar rad. pressure model	Bus
TDRS area	40 m^2
TDRS mass	1807 kg
GPS solar rad. pressure model	T10/T20
Polar motion (X,Y)	IERS-B
Earth rotation (UT1 - UTC)	IERS-B
Station locations (TurboRogues)	ITRF'91
White Sands station location	WGS-84
Earth gravity field	JGM-3 (12X12)

The TDRS phase data were modeled as 3-way measurements (i.e. 2 legs and 3 participants). Although it is instructive to think of TDRS as the originator of the signal (in the manner of GPS), this is not strictly correct. The signal originates at White Sands, and is transmitted to TDRS which serves as a "bent-pipe" transponder, redirecting the signal to the ground. It follows that we do not solve for the TDRS clock offset in our orbit determination procedure, but rather the offset of the master frequency generator on the ground at WSGT. This modeling ensures that the Doppler signature from the uplink is handled properly, i.e. it is not incorrectly absorbed in the TDRS clock solution. The range data from WSGT were modeled as simple 2-way measurements.

Station coordinates for the TDRS/GPS terminals in El Paso, Socorro and Pasadena were fixed at precise values determined a *priori* using the GPS data collected at the sites. In this exercise, data from a small subset of the global GPS network were used to augment the 3-station TDRS network. These stations, whose positions are known at the cm level relative to the geocenter [e.g., 17], served as fiducial points for registering the TDRS stations to the International Terrestrial Reference Frame (ITRF). The GPS solutions for the station coordinates appear to be quite accurate: for the 260 km El Paso to Socorro baseline, the repeatability of daily solutions is about 2-7 mm in all components; for the 1000-km lines between Socorro/El Paso and JPL, the repeatability also is sub-cm in all three components. For the 18-m WSGT antennae that collect the range data, we used coordinates provided by NASA in the WGS-84 system. We did not have a GPS receiver at WSGT and therefore were unable to estimate improved coordinates, Any error in this station coordinate will manifest itself as a range bias, which we estimated via external calibration (as described in the previous section).

RESULTS FOR TDRS-3 CONTINUOUS TRACK

We focus first on a 19-hr span of data on January 19 during which all three stations tracked TDRS-3 without a single loss of lock or cycle slip (compare Figure 2). This implies that a single phase bias can be estimated over the entire arc for each station/TDRS pair. Our initial solution used only the TDRS tone data + GPS pseudorange and carrier phase. In subsequent variations, we added the WSGT range (both raw and calibrated). Before evaluating directly the accuracy of the estimated TDRS orbits, we examine the solutions for some of the ancillary calibration parameters, such as those associated with the clocks and troposphere delay. These parameters are determined almost entirely from the GPS data, and our tests suggest that their estimates are not significantly altered by the presence of TDRS data in the solution,

CALIBRATION PARAMETERS

Shown in Figure 6 are the estimated clock offset (relative to our reference clock at, El Paso) of the GPS station at Socorro. Evident in the clock solutions for the TurboRogues are the effects of the internal clock steering, The receivers used in this demonstration were not connected to external frequency standards, but their internal oscillators are steered using GPS point positioning solutions to keep them reasonably close to GPS time. While the actual clocks wander by 2–4 µs in extreme cases, the formal errors on the estimates of the offset at each measurement time are typically 0.1 to 0.2 ns. Assuming the formal errors are optimistic, and the clock errors are actually closer to 1 nsec, the effect on the TDRS phase may be as huge as 30 cm. However, to the extent that the error reflects a constant bias between two stations over the entire arc, the error is of no consequence. Recall *that SB*$\Delta\Phi$ makes no attempt to resolve the phase biases between stations. It is therefore not sensitive to an initial clock difference, but rather to the stability in the uncalibrated clock differences over the course of the orbit arc.

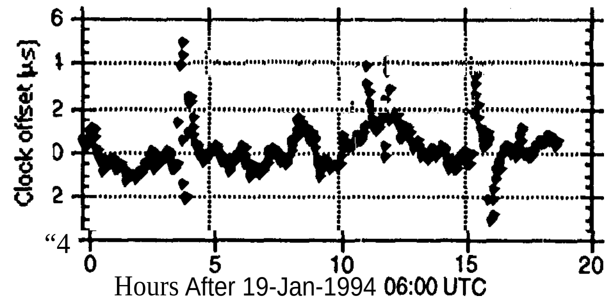

Fig 6. Estimates of clock **offset for TurboRogue at Socorro, New Mexico, relative to El Paso, Texas, on January 19,1994, The RMS of the clock offset 1s -1 µs and the variations result from internal clock steering. Formal errors on the estimates are ~ 0.1 ns, suggesting that very tight clock synchronization is possible over this 260 km baseline,**

Figure 7 gives the estimated zenith wet-troposphere delay at Socorro. These values are mapped to the line-of-site to TDRS in correcting the phase data. The formal errors in these estimates are at the cm-level,

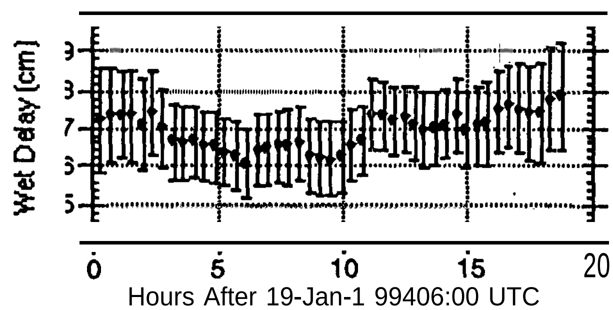

Fig 7. Estimates of the zenith wet troposphere path delay at Socorro, New Mexico, on January 19, 1994. These values, based primarily on simultaneous observations of multiple GPS spacecraft, are mapped to the line of sight to TDRS to correct the phase data.

POSTFIT RESIDUALS

The root-mean-square (RMS) post-fit observation residuals for the TDRS and GPS phase measurements were 2.6 and 2.8 mm respectively. That the TDRS phase data can be fit as well as the GPS phase is encouraging, and suggests that the TDRS data quality is excellent. The

GPS pseudorange, which is important for determining the clocks offsets, was fit to 0.3 m (RMS). In the cases where the TDRS 2-way range were included, these observations were tit to about 3 m (RMS). While these numbers are instructive for estimating bounds on the measurement noise, they reveal little about the orbit accuracy. For this, we examine the formal errors of the TDRS orbit solution, and compute differences with respect to the BRTS-derived orbit from GSFC.

FORMAL ORBIT ERRORS

Formal errors of the orbit solution for TDRS-3 were mapped over the entire 19-hour arc, and the results are summarized in Figure 8. Two solution strategies reflecting different observation sets for TDRS are considered: 1) TDRS phase + WSGT range, and 2) TDRS phase + calibrated WSGT range. In the first case, a 50-m *a priori* uncertainty (1 σ) was assigned to the range bias (1 leg), while in the second case, this was reduced to 1 m. We note that there is essentially no information for the estimation of the bias; it serves only to inflate the formal errors in the down-track (inertial) component so that they are more realistic. The sensitivity of the down track error to the range bias is clearly illustrated in the figure. This error is almost entirely a bias, so the orbit is simply shifted in longitude by about 0.5 km. The height and cross-track are well determined in both cases, with RMS formal errors in the range of 1 to 5 m. In the second case, where the calibrated range data are used, the total root-sum-square (RSS) 3-dimensional position error is reduced to less than 20 m.

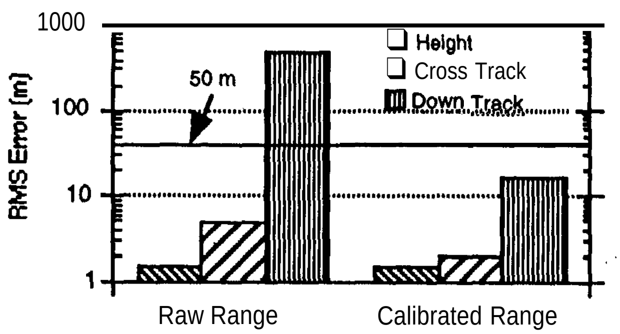

Fig 8. RMS formal **errors for TDRS-3 orbit using 1) phase + raw WSGT range and 2) phase + calibrated WSGT range. The short. baseline differenced phase and coarse range data are adequate to determine all components of the TDRS orbit except for the longitude (down-track). Better range data can control the longitude error.**

COMPARISONS WITH BRTS ORBITS

While the formal errors from the solutions are, instructive for characterizing the. general behavior of the orbit errors, it is important to note that they may represent underestimates of the actual orbit error, and thus should be interpreted with caution, Systematic error sources, such as those due to unmodeled solar radiation pressure effects, non-random variations in the tracking observations, and errors in Earth rotation and orientation parameters can augment considerably the actual orbit error. A better measure of the orbit accuracy is thus gained from external comparisons. To this end, we compared our January-19 solutions against the precise BRTS-derived orbits. These orbits are thought to be accurate to 50 m or better in total position (1-σ).

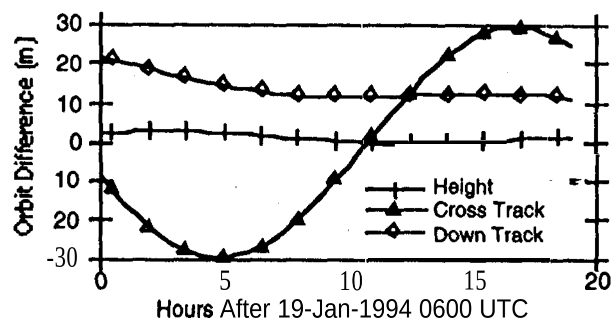

Fig 9. Ttme series of **TDRS-3** orbit **differences (this study vs. BRTS orbit from Goddard Space Flight Center) for January 19, 1994. The RMS differences in height, cross track, and down track are 1.6 m, 22.4 m and 14.2 m respectively.**

Figure 9 shows the difference of our solution for TDRS-3 and the BRTS orbit for the 19 hour continuous arc on January 19. For this comparison, our orbit is the one corresponding to the second case above (i.e., TDRS phase + calibrated WSGT range). The calibration of the range data was performed by removing *a priori* a 54.1 m delay (l-leg) from the WSGT range data (compare Figure 5). The rms differences in height, cross and down track are 2, 22, and 14 m respectively, This level of agreement is considered quite encouraging, and was somewhat unexpected given published estimates of the errors in the BRTS orbits, It should be remembered, however, that the down track component of our orbit (i.e. longitude) is constrained to match the BRTS orbits in the bias term via the range calibration. Without the 54.1 m range calibration, the down-track bias increases to 0,7 km (consistent with the formal error), but the variation of the down-track about this bias is unaltered. The RMS height difference remains under 2 m, and the cross track is still sub 30 m (RMS). These results corroborate the conclusion of *Nandi et al. [11]* that even coarse range data, when blended with SBΔΦ measurements, are adequate to ensure a precise determination-excepting *a* simple bias in longitude-of the TDRS orbit. This final indeterminacy can be removed by using a few well-calibrated ranges.

EXTENDED RESULTS

Building on the solution strategy that evolved from our evaluation of the continuous arc for TDRS-3, we have processed the data from much of the remainder of the experiment. The main challenge here was devising a method to properly handle TDRS phase breaks and potential cycle slips within the arc (compare Figure X). To address this problem, we used an iterative procedure wherein successive passes through the filter were used to examine postfit phase residuals. Known phase breaks (i.e. the receiver lost lock and the cycle count restarted at O) were flagged before the first pass through the filter. In subsequent iterations, a decreasing threshold on the maximum difference between adjacent postfit residuals were used to flag potential cycle slips. Some undetected cycle slips were identified using this procedure, but they usually occurred in the vicinity of a receiver loss of lock. For every loss of lock or cycle slip, the phase bias is re-estimated. This weakens the solution somewhat, but as borne out in our results, does not severely compromise the orbit accuracy unless the breaks are quite numerous.

A total of four orbit arcs were considered: three for TDRS-3 and one for TDRS-5. The arc lengths vary from 18 to 21 hours and span the period from January 1906:00 UTC to January 2213:00 UTC. (The first arc is actually the same one evaluated extensively in the previous section). For the TDRS-3, the calibration correction of 54.1 m was applied *a priori* to all the range data. For TDRS-5, which was tracked from a separate antenna at WSGT, range data were not available at this writing. Pending receipt of these data, we simulated range measurements from WSGT using the BRTS orbit from GSFC.

Shown in Figure 10 is a bar graph with the formal errors for the four solutions. Is can be seen that the RMS errors from the continuous arc are representative of the other arcs as well. The maximum 1 σ formal error over the .-3-day span is 21 m. Figure 1,1 gives the RMS differences with respect to the BRTS orbits for the same solutions, The RMS differences range from 1 to 9 m in height, 13 to 30 m in cross track, and 14 to 30 m in down-track, and the maximum difference over the entire ~3 day span is 52 m. Especially encouraging are the results for TDRS-5, which was tracked at a much lower elevation than TDRS-3. Moreover, the signature that TDRS-5 traced in the plane of sky was very compact compared to the one for TDRS-3. Despite these important differences, the TDRS-5 orbit accuracy appears only slightly degraded and readily satisfies our 50-m requirement.

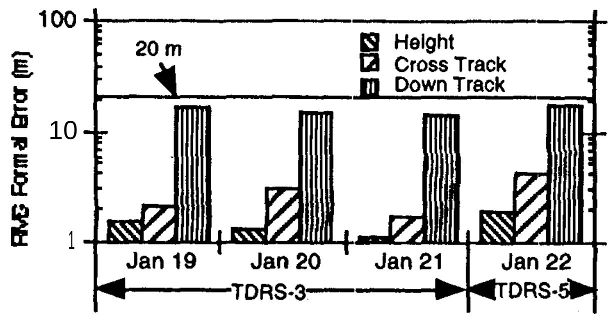

Fig 10. Bar graph showing RMS formal errors of TDRS orbit solutions computed as part of this study. The first three solutions correspond to TDRS-3 and the last to TDRS-5. The arc lengths vary between 18 and **20** hours in length,

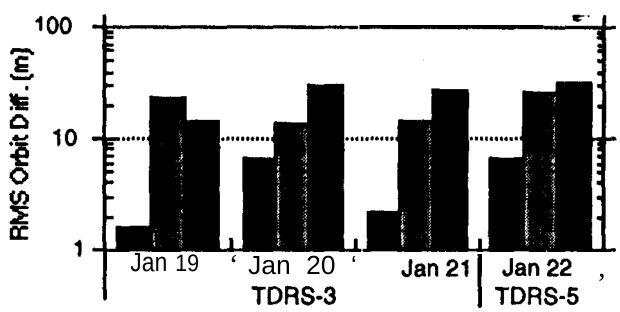

Fig 11. Bar graph summarizing RMS TDRS orbit differences (this study vs. BRTS). he first three solutions correspond to TDRS-3 and the last to TDRS-5. The arc lengths vary between. 18 and 20 houra in length. The largest excursion over the entire set of comparisons is 52 m.

DISCUSSION

These results suggest that under nominal conditions the short-baseline GLT method can be used to deliver TDRS orbits with accuracies better than 50 m in total position. In an actual operational scenario, it would be necessary to obtain these results in real time. In this context, we note that entire orbit determination procedures were run on HP workstations, and that the sequence of programs required to generate an ephemeris file consume a cumulative CPU time of only a few minutes. These program sequences can be automated, as has been done for computing Topex/Poseidon orbits [21). In a recent demonstration of the Topex/Poseidon automated system, orbit estimates were delivered within 24 hours of the receipt of the flight data, For this exercise, a combination of orbit fits and predicts permitted achievement of radial accuracies better than 1 m in real time.

For the TDRS study, there are still some outstanding operational issues that should be addressed. We plan to perform another demonstration of the system, and we will deploy all the stations around White Sands within the main beam of the SGLS. The accuracy should be somewhat degraded for these shorter baselines, but covariance analyses suggest that the 50 m requirement can still be met [11]. Another issue is the availability of well-calibrated range data from WSGT. A new second-generation ground terminal is undergoing testing at White Sands, and the ranging data from there should be improved. Lacking accurate enough data with the new system, a calibrated measurement might be obtained by tapping into the uplink and down link at White Sands with a TurboRogue receiver. Finally, it will be necessary to demonstrate that the 50-m accuracy can be achieved within 2 hours after a station-keeping maneuver. This would involve modeling the maneuver within the orbit arc, since the short-baseline difference phase data is not strong enough to recover the trajectory from a cold start in 2 hours [11], In the simplest approach, a velocity impulse could be estimated at the bum time [11].

If these issues can be put to rest, then the short-baseline GLT method offers some distinct advantages for future TDRS tracking. Among them are: 1) low-cost of the small antennae and GPS receivers in comparison with larger systems typically used for geosynchronous tracking; 2) accuracy rivaling connected element networks for the calibration of media, Earth platform and timing errors from the simultaneous observation of TDRS and GPS; 3) operational convenience and maintainability afforded by a small, simple tracking stations in the vicinity of White Sands (as opposed to the present global network); and 4) processing system that lends itself to a high-level of automation, even on a desk-top work station.

Similar benefits could be shared by other future missions adopting the GLT technique. In the case of the NASA Deep Space Network, which supports high-Earth orbiters in addition to deep space probes, valuable large antenna time could be freed up for more dedicated interplanetary tracking sessions, The high potential for inexpensive tracking should also be attractive to designers of NASA, military and commercial systems used for orbit determination of geosynchronous satellites.

ACKNOWLEDGEMENTS

The work described in this paper was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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